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A NEW SIMULATOR FOR ASSESSING SUBJECTIVE EFFECTS OF SONIC BOOMS

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SUMMARY

A man-rated and computer-driven sonic boom simulator, which has been constructed and placed in operational use at NASA Langley Research Center, is described. The simulator is used to study human subjective reactions to sonic booms and has the capability of producing a wide range of boom signatures under controlled conditions. Results are presented to illustrate the capability of the simulator to generate user-specified N-wave and other boom shapes having rise times as low as 0.5 milliseconds and peak overpressures up to 191 Pa (4 psf).

The validity of the simulator as a laboratory research tool for studying human subjective response to sonic booms was demonstrated by successful completion of a preliminary test designed to compare loudness of N-wave sonic booms with results obtained by other investigators. Excellent agreement of the preliminary test data with existing data was observed. This provided confidence in the experimental methodology and established the simulator as a viable tool for performing detailed evaluations of sonic boom loudness and acceptability within the laboratory environment.

INTRODUCTION

The proposed development of a second generation supersonic transport has resulted in increased research efforts to provide an aircraft that will have no harmful effect on the atmosphere. In addition these efforts will address the feasibility of modifying aircraft design and operations to produce boom signatures that will have minimal impact on the public. This approach will involve tailoring the aircraft volume and lift distributions to produce boom signatures having specific shapes that may be more acceptable to the public and could possibly permit overland supersonic flight. As part of these efforts the Langley Research Center has initiated a program to investigate subjective response due to sonic booms presented in both indoor and outdoor listening situations. This program will provide data for use by researchers in the assessment of subjective acceptability of candidate "minimum boom" aircraft configurations and will involve both laboratory and field studies. To accomplish this program Langley Research Center has designed and constructed a computer-controlled, man-rated sonic boom simulator capable of reproducing user-specified pressure signatures for a wide range of sonic boom parameters (e.g., rise time, overpressure, duration). Laboratory studies, although not always entirely representative of real world situations, do provide a controlled environment for exploring subjective reactions to sonic booms having specified signatures.

Previous research (references 1-4) has demonstrated that a small, loudspeaker-driven booth provides a viable approach to sonic boom simulation. These previous simulators, none of which now exist, were of sufficient volume to

accommodate one test subject, were essentially airtight, and had rigid walls. These latter two characteristics were necessary to generate the very low acoustic frequencies present in sonic booms. Pearsons and Kryter (reference 1) used a simulator constructed of concrete blocks and equipped with five 46-cm diameter low frequency loudspeakers. It had a volume of 2.75 m^3 and was able to achieve a peak overpressure of about 200 Pa (4.2 psf). Two other simulators (references 2 and 3) were of similar design but were restricted in their ability to achieve short sonic boom rise times due to the limited high frequency response of large loudspeakers. Glass, et al. (reference 4) demonstrated that a combination of low frequency and mid frequency loudspeakers was capable of producing simulated sonic booms with rise times less than 1 msec.

All simulators of this type have an inherently non-uniform frequency response due to the complex interaction between the loudspeakers and the enclosed volume of air. Previous investigators attempted to overcome this deficiency by using many filters, typically of one-third octave bandwidth. Niedzwiecki and Ribner (reference 5) employed a different technique which required that the boom signatures be synthesized, rather than be true sonic boom recordings. Their technique involved altering the electrical input signal spectrum using the inverse of the complex frequency response of the simulator. In other words the electrical input signal was pre-distorted to compensate for non-uniformities in the loudspeaker-booth transfer functions. This technique was used successfully.

In most instances previous investigators played the sonic boom signatures from an FM tape recorder. The limited dynamic range typical of this method resulted in high levels of background noise (tape hiss) and led some investigators to employ squelch circuits to reduce the noise between sonic boom presentations.

The design of the NASA Langley Research Center simulator was based upon the pre-distortion schemes described in the earlier efforts. However, attempts were made to overcome some of the previous deficiencies through application of recent advances in electronic and computer technology.

The specific objectives of this report are to: (1) describe the new Langley Research Center sonic boom simulator; (2) document the simulator performance for N-wave and shaped boom signatures; and (3) discuss the results of a preliminary test conducted to validate experimental methodology as well as provide subjective data for comparison with the results obtained by prior investigators.

SONIC BOOM SIMULATOR

Simulator Description.- The Langley sonic boom simulator (see figure 1) has walls of 20-cm thick concrete block and a concrete ceiling and floor of thicknesses 13 cm and 10 cm, respectively. The acoustical door is of foam-filled construction and has edge seals to maintain the booth as airtight as possible. The internal dimensions of the booth are 1.52 m high, 0.96 m deep, and 1.07 m wide, yielding a volume of 1.6 m^3. To reduce the effects of acoustic resonances, the floor is carpeted and the

interior walls and ceiling are covered with 10-cm thick acoustical foam. This reduces the volume to about 1.1 m. One wall contains a small window made of 2.5-cm thick Plexiglas. The edges of this window and the electrical wiring access holes were sealed with caulking material to maintain an airtight booth. The volume of air contained within the booth is sufficient to sustain a single individual more than eight hours. The simulator door contains eight loudspeakers, four 38-cm low-frequency units (JBL Model 2235H) and four 18-cm mid-range units (Audax Model PR17HR100). The speakers are protected from possible damage by a perforated metal screen.

The major elements of the sound generation and monitoring system are indicated in figure 2. The input signal originates from a computer- driven, 16 bit, digital to analog converter and is then low-pass filtered to remove the digitizing frequency from the signal. A crossover network (crossover frequency set at 420 Hz) separates the high and low frequency components of the signal for input into the high and low frequency loudspeaker systems. Each set of four loudspeakers, connected in parallel, is powered by a DC-coupled amplifier (B&K Model M200) rated at 200 watts when driving an 8 ohm load. For the reduced load of this loudspeaker arrangement, and for a low duty cycle as required for sonic boom testing, the amplifiers are capable of generating more than 1000 watts.

Since the simulator was designed for use in human subjective response testing it was necessary to incorporate various safety features into its design. One such feature is a laboratory-mandated level limit for peak sound pressure of140 dB and an A-weighted limit of 95 dB(A) for human testing. To fulfill this requirement two microphones located in the simulator and two sound level meters were used to monitor the sound levels. If the sound level meters detect a level more than the 140 dB or 95 dB(A) limits, the input to the simulator is interrupted. Other features incorporated into the design of the simulator include the provision of a two-way intercom and closed circuit television for test subject monitoring.

A special low-frequency microphone with frequency response down to 0.10 Hz was used to obtain measurements of the pressure signatures produced within the booth. Analog to digital conversion of the measured signals was then performed and the digital information used to calculate sound levels in terms of several metrics (to be discussed later) and to characterize the measured signatures.

Simulator Performance.- A key performance characteristic for a sonic boom simulator is its low frequency response. Since a typical sonic boom has its maximum acoustic energy at a frequency of approximately 2-3 Hz, the simulator has to be an essentially airtight, rigid enclosure. Figure 3 illustrates the frequency response of the simulator at low frequencies (0.1-10 Hz) as measured by a microphone positioned at the head location for a seated subject. This figure shows that between frequencies of 0.7 and 10 Hz the response is flat, within ±1 dB. At frequencies below about 0.7 Hz the response decays at 6 dB per octave. As will be illustrated later, this low frequency performance is adequate for sonic boom simulation.

At higher frequencies, the complex interaction between the loudspeakers and the enclosure results in a highly non-uniform frequency response. This is illustrated

in figure 4, which shows the frequency response to be greatest at low frequencies, with a general decrease in response with increasing frequency. Superimposed on this trend are numerous peaks and valleys resulting from acoustic resonances within the enclosure. A later section will discuss the approach undertaken to modify the simulator drive signal to overcome these deficiencies.

The maximum acoustic pressure that can be generated in the simulator is obviously frequency dependent. The choices of the number and type of low frequency loudspeakers, and the size of the enclosure, were based on a desire to produce sonic booms with overpressures of approximately 191 Pa (4 psf), which is equivalent to a peak sound pressure level of 139 dB. As mentioned earlier, the laboratory limit for exposure of test subjects is 140 dB. Using synthesized sonic booms, the simulator was found to be capable of generating signatures at levels up to 140 dB.

Background noise, which can contaminate the sound measured within the simulator, consists of two components: noise generated within the building, such as that produced from air handling equipment, and noise generated within the sound reproduction system. Figure 5 shows a one-third octave band spectrum of the noise measured in the simulator when the sound system was switched off. For this condition the measured level was 34 dB(A). When the sound system was switched on, the level increased to 40 dB(A). The corresponding one-third octave band spectrum is presented in figure 6. This level is considered acceptable for sonic boom testing.

<u>Sonic Boom Synthesis Method</u>.- Because of nonuniform frequency and phase response characteristics of the simulator the boom signatures within the simulator may bear little resemblance to the electrical input analog of the desired signature shapes. To correct this situation it was necessary to "pre-distort" the signals applied to the loudspeakers to produce the desired boom signatures within the simulator. The concept of predistortion of the input signals was applied in earlier research efforts (references 4 and 5) with good success. Their approach was to modify the electrical input signal using the inverse of the complex frequency response of the simulator. The present study used a similar approach but incorporated recent advances in electronics, computer, and digital filtering. To obtain an undistorted sonic boom in the simulator requires a broadband equalization filter with good frequency resolution and good low frequency response. To meet this requirement a digital broadband equalization filter was designed using a time domain method. The time domain method used was the Widrow-Hoff least mean- square (LMS) adaptive algorithm. Discussion of this method is beyond the scope of this paper but is described in detail in reference 6.

A computer program (not discussed herein) was developed to allow the test conductor to specify in detail the desired sonic boom time histories to be generated within the simulator. These time histories were processed through a time domain equalization filter, as described above. Output of the equalization filter was the digital form of the predistorted time history. This digital time history was then applied consecutively to a D/A converter, smoothing filter, analog attenuator, crossover network, loudspeaker amplifiers, and simulator loudspeakers.

Examples of three sonic boom signatures (two N-wave, one shaped) at several stages during the synthesis process are presented in figures 7(a)-7(c). Shown are the desired signatures (provided to the computer), the predistorted signatures (output of equalization filter), and the signatures measured within the simulator. The center group of figures indicate that significant distortion of the desired signals was required to compensate for the nonuniformities in the simulator transfer functions and to produce the signatures measured within the simulator shown in the group of figures on the right.

PRELIMINARY SUBJECTIVE RESPONSE TEST

Upon completion of the sonic boom simulator performance tests, a preliminary subjective response study was conducted to provide additional checkout of hardware performance and to validate experimental methodology and test procedures. This study also provided data for comparison with previously published results of other researchers (references 5 and 7). Successful replication of results obtained in prior studies would provide increased confidence in the validity of the simulator as a useful tool for assessing sonic boom subjective effects.

Description of Test.- Based upon a review of the earlier literature it was decided to conduct a test similar to the two studies described in references 5 and 7. Those tests determined subjective response to both N-waves and shaped booms. (Boom shaping involves tailoring the shape of a boom signature in a manner that will tend to reduce boom loudness.) In those studies the method of paired comparisons was used to determine the relative effects of rise time, peak overpressure, and duration upon subjective loudness judgments obtained within the laboratory. These effects were defined in terms of equal loudness contours from which rise time versus peak overpressure tradeoffs could be readily determined. The present preliminary test investigated a limited range (as compared to the above studies) of rise time and peak overpressure and held duration constant. Details of the stimuli used and experimental approach are presented in the following sections.

Experimental Approach.- Thirty-two test subjects (16 males, 16 females) obtained from a subject pool of local residents were used in the preliminary study. None of the subjects had prior experience in subjective response testing involving impulsive-type sounds. All subjects were required to undergo audiometric screening to insure normal hearing.

The psychometric method used in the test was the method of paired comparisons. This method involved presentation of pairs of boom signatures to each subject (one subject at a time), with one member of a pair always being a pre-selected "standard" signature. Upon listening to a boom pair a subject was required to indicate which of the two signatures was the loudest. For this study the "standard" boom signature was an N-wave with a duration of 300 ms, a rise time of 3 ms, and a peak overpressure of 49 Pa (1.03 psf). Comparison signatures (that is, the other member of each boom pair) consisted of both N-waves and shaped signatures having a fixed

duration of 300 ms. Sketches of an N-wave and a shaped boom signature are presented in figure 8 to illustrate the definition of rise time and peak overpressure for each boom type. The N-waves had rise times of either 1, 2, 4, or 8 ms. The shaped signatures had initial and secondary rise times (see figure 8) of 2 ms and 50 ms for the initial (ΔP_I) and secondary shocks respectively. Peak overpressure (ΔP_{max}) for both N-wave and shaped signatures was the absolute maximum overpressure over the signature time history. Two shaped signatures were investigated, one with $\Delta P_I/\Delta P_{max} = 0.25$ and the other with $\Delta P_I/\Delta P_{max} = 0.50$.

The parameters of the comparison boom signatures selected for the test are summarized in table 1. The peak overpressure levels for each signature are denoted by the integers 1 through 6 since the ranges of actual overpressure values for each signature were, of necessity, considerably different from one another to permit development of equal loudness contours. Factorial combinations of the boom parameters of table 1 result in 36 comparison signatures. To minimize order effects the standard signature was presented as both the first and second stimulus within a pair. This resulted in a total of 72 stimulus pairs. These were randomized and divided into two test sessions of 36 stimulus pairs each. To further minimize order effects, the test sessions were interchanged and presented in forward and reverse sequence from subject to subject. This resulted in four different presentation orders of the stimuli pairs with every fourth test subject receiving the same order of presentation.

Test Procedure.- Upon arrival at the laboratory, the subjects were briefed on the overall purpose of the test, the test procedure to be followed, system safety features, and their rights as test subjects. A copy of the briefing remarks is given in Appendix A. They were then asked to read and sign a voluntary consent form (see Appendix B). The subjects were then taken individually to the simulator and given instructions regarding the specific tasks required in the tests. A copy of these instructions is presented in Appendix C.

Before entering the simulator, each subject was asked to listen to several pairs of boom signatures, played with the simulator door open, to become familiar with the types of sounds they would be required to evaluate in the test. At this point they were given a practice scoring sheet and seated in the simulator with the door closed. A series of six practice booms was presented and the subjects were asked to indicate on the scoring sheet which sound of each pair was the loudest. Upon completion of the practice session, the scoring sheets were collected and any questions regarding the scoring procedure were answered. Scoring sheets for the first test session were then distributed and the first session conducted. This was followed, after a brief break, by the second test session. Samples of the practice scoring sheets and the test session scoring sheets are given in Appendix D.

Data Analysis.- Sonic boom signatures were measured with the simulator empty using a special low-frequency microphone located roughly at ear level for a seated subject. These measurements were computer-processed to calculate sound levels in terms of several noise metrics including: Perceived Level (PL), A-weighted level sound pressure level (SLA), and C-weighted sound pressure level (SLC). The Perceived Level (Steven's Mark VII) loudness calculation procedure extends to very

low frequencies typical of most sonic boom signatures. The calculation procedures are described in reference 8. Unfortunately, the special low frequency microphone had a significant high frequency noise floor that introduced errors in the calculated metrics, which are sensitive to the high frequency components. Thus a second microphone having a very low noise floor, but limited low frequency response (3 Hz), was used to obtain measurements for use in calculating SLA and PL.

The primary parameter of interest in the subjective rating data was the proportion (or percentage) of responses, for each comparison boom signature, that were rated as being louder than the standard boom signature. Regression analysis was then performed to relate the subjective judgments to each of the noise metrics described earlier as well as to peak overpressure. The resulting regression equations could then be used to determine values of the three noise metrics (PL, SLA, SLC) and peak overpressures of each comparison boom signature that were equal in loudness to the standard boom signature. Since the dependent variable in this study was dichotomous, it was necessary to formulate the regression equation to vary between 0 and 1 (since we were dealing with proportions). This was accomplished by using logistics regression analysis (see reference 9). The distribution used to model the expected value (that is, conditional mean) of a dichotomous variable is the logistic distribution. For this distribution the binomial, not the normal, distribution describes the distribution of the errors and is the statistical distribution upon which the analysis is based. The specific form of the logistic regression model used was

$$\Pi(x) = \frac{e^{\beta_o+\beta_1 x}}{1+e^{\beta_o+\beta_1 x}}$$

where $\Pi(x)$ is the proportion of judgments indicating a comparison boom was louder than the standard for a given peak overpressure or metric level denoted by x. (Note that x is the independent variable in the logistic regression analysis.) The parameters β_o and β_1 are parameters determined by fitting the regression model. They are obtained by applying the logit transformation, g(x) (see reference 9), given by

$$g(x) = \ell n\left[\frac{\Pi(x)}{1-\Pi(x)}\right] = \beta_o+\beta_1 x$$

This transformation is linear in its parameters, may be continuous, and may range from $-\infty$ to $+\infty$, depending on the range of x. This allows application of the maximum likelihood method to determine the maximum likelihood least squares estimators of the parameters β_o and β_1.

DISCUSSION OF RESULTS

The loudness judgments were used to calculate the percentage of subjects who rated the comparison boom as louder than the standard boom for each boom pair. A "percent louder" value of fifty percent represents the value at which the comparison

booms were considered equal in loudness to the standard boom. The "percent louder" values for each comparison boom signature are presented in figure 9(a)-9(d) as a function of peak overpressure (in decibel units, i.e., 20LOG (ΔP_{max})), SLC, SLA, and PL. The strong dependence of subjective loudness on the parameters of rise time and peak overpressure is illustrated in figure 9(a). Subjective loudness generally increased with peak overpressure for all boom signatures and, for a specific overpressure value, varied systematically with rise time for the N-wave signatures. Consider, for the N-wave signatures, the values of peak overpressure that would produce subjective loudnesses equal to the loudness of the standard signature. These values are obtained by determining the intersection points of the horizontal dashed line in figure 9(a) with each of the N-wave curves (indicated by rise times of 1, 2, 4, and 8 ms). The horizontal line represents a percent louder value of 50 percent, which corresponds to the classical definition of a subjective equality point. For N-wave signature rise times of 1, 2, 4, and 8 milliseconds the respective approximate peak overpressures corresponding to the intersection points were determined to be 0.56, 0.81, 1.07, and 1.70 psf (27, 39, 51, and 81 Pa). Thus, for the N-wave boom signatures, peak overpressure must increase with increasing rise time to maintain constant loudness. This implies that, for constant peak overpressure, signatures having longer rise times would be more acceptable. Similar results have been observed previously (see reference 7, for example).

Comparison of Metrics.- Figures 9(b)-9(d) present the same subjective data in terms of the three selected metrics. Figure 9(b) shows that SLC only slightly narrows the "spread" between the data for the six signatures. Figures 9(c) and 9(d) show that the scatter in the data was substantially reduced by the SLA and PL metrics. These results indicate that the SLA and PL metrics were effective in accounting for the difference in boom parameters for both boom types.

The correlation coefficients between the "percent louder" scores and each noise metric and between the calculated logit scores and each metric are given in table 2. These coefficients were calculated using results for the individual boom signatures (booms 1-6) and for the results pooled over all signatures. For the individual comparison boom signatures the correlation coefficients are all high with no significant differences between metrics or between coefficients obtained using the calculated proportions (untransformed scores) and using the logit scores. This result was not unexpected since consideration of individual signatures eliminated the effects of rise time, which was a major source of variability. Analysis of the pooled data, however, indicated that the SLA and PL metrics performed significantly better than SLC, with PL having slightly higher correlations than SLA. This further demonstrates that both SLA and PL effectively accounted for rise time effects and the differences in shapes of the N-wave and "shaped" signatures.

The 95 percent confidence intervals associated with the proportions (that is, proportion of responses that rated a comparison signature louder than the standard signature) for each boom signature are presented in figures 10(a)-10(f) in terms of PL. At the equal loudness level (percent louder = 50) these confidence intervals fall within a range of approximately ±1 dB in terms of PL.

COMPARISON WITH PRIOR RESEARCH

It was of interest to compare results obtained in the present study with similar laboratory data obtained by prior investigators. Favorable comparison would provide further validation of the NASA simulator and would permit the NASA sonic boom research effort to build upon, and not replicate, prior results. The data selected for comparison was taken from figure 7 of reference 7 and consists of an equal loudness curve based on data obtained by several earlier investigators showing the tradeoff between overpressure and rise time for 200 millisecond duration N-waves. The standard boom signature used in reference 7 had a rise time of 1 millisecond and a peak overpressure of 48 Pa (1.0 psf). The standard signature for the present study had a rise time of 3 milliseconds and a peak overpressure of 49 Pa (1.03 psf). Thus, to make comparisons with the results of the present study, it was necessary to adjust the data from reference 7 to account for the difference in rise time. The procedure used to adjust the reference 7 data is summarized as follows: It was determined that the constant loudness curve of reference 7 was approximately linear for a range of N-wave rise times of 1 to 10 ms. Based on this, the increment in overpressure required to maintain constant loudness between a rise time of 1 ms (reference 7 standard boom) and a rise time of 3 ms (standard boom in current study) was determined. This increment in overpressure was then subtracted from the reference 7 curve. This effectively resulted in a new equal loudness curve having loudness equal to that of the standard boom signature used in the present investigation. The resultant comparison of the two curves is presented in figure 11. The agreement between the two sets of results is excellent and demonstrates the reliability and consistency of human subjective loudness judgments, even when obtained years apart and within different experimental situations.

BOOM SHAPE EFFECTS

The constant loudness curve of figure 11 was in terms of peak overpressure and rise time. Similar curves for the three calculated metrics are presented in figures 12(a)-12(c) for the N-wave signatures. Also shown in each figure are the ±1 standard deviation boundaries for each constant loudness curve. These data show that PL was most effective in accounting for the effect of rise time as indicated by the relative flatness of the PL constant loudness curve as compared to the constant loudness curves of the other metrics. The SLC and SLA curves exhibit an increasing and decreasing trend, respectively, with rise time. These trends reflect the combined effects of reduced high frequency spectral content (for the longer rise times) and the respective A and C frequency weightings. These data imply that PL may be a better metric than SLA and SLC even though the correlations (table 2) between the individual metrics and subjective loudness did not differ significantly for individual boom shapes.

The six boom signatures that were rated equally loud as the standard boom are shown graphically in figure 13 and clearly illustrate the tradeoffs between rise time and peak overpressure for the N-wave signatures. For example, an N-wave having

a rise time of 8 milliseconds and a peak overpressure of 81 Pa (1.7 psf) is equivalent in loudness to an N-wave with rise time of 1 millisecond and peak overpressure of 27 Pa (0.56 psf). In this case increasing rise time from 1 to 8 milliseconds would permit peak overpressure to increase by a factor of three without an increase in loudness.

Inspection of the two equally loud minimized signatures in figure 13 shows that the second shaped boom (min B) had a significantly higher peak overpressure than the first shaped boom (min A). The initial shocks for the two shaped booms, however, were approximately equal. This implies that loudness for the shaped signatures was primarily determined by the initial shocks. Note also that the peak overpressure for the second shaped signature was approximately 4.6 times larger than that of the 1 millisecond rise time N-wave signature. Thus the shaped signature could tolerate substantially higher peak overpressures for equivalent loudness. This illustrates one of the important potential advantages to be gained by boom shaping. This result was to be expected based on earlier observations (reference 5) and loudness calculations (reference 8) and illustrates the important potential advantages to be gained by boom shaping.

CONCLUDING REMARKS

As part of the NASA Langley Research Center sonic boom program a man-rated and computer-driven sonic boom simulator booth has been constructed and placed into operational use. The simulator is used to study human subjective reactions to sonic booms and has the capability of producing a wide range of signatures under controlled conditions. It employs sophisticated time domain filtering algorithms to pre-distort the input waveforms (desired boom signatures) to compensate for non-uniformities in simulator frequency and phase response and accurately replicate the desired signatures within the booth. An extensive series of measurements taken within the simulator demonstrated the capability of the system to generate user-specified N-wave and minimized boom signatures having rise times as low as 0.5 milliseconds and peak overpressures up to 191 Pa (4 psf).

Results obtained in the preliminary tests showed that loudness level, PL, performed slightly better than SLA and much better than SLC as a loudness estimator for the range of boom parameters considered. It effectively accounted for both rise time and peak overpressure effects. However, the preliminary test included only a small selection of boom parameters and shapes. Additional research is required to determine whether this result remains valid for a larger range of boom parameters.

The validity of the simulator as a laboratory research tool for studying human subjective response to sonic booms was demonstrated by successful completion of a preliminary test designed to replicate subjective results obtained by earlier investigators. Excellent agreement of the preliminary test data with the existing data was observed. This provided confidence in the experimental methodology used in the present test and established the simulator as a viable tool for performing detailed evaluations of sonic boom acceptability within the laboratory environment.

Specific results obtained in the preliminary test confirmed that sonic boom subjective loudness depended upon both rise time and peak overpressure. Increasing peak overpressure increased subjective loudness for all boom signatures as would be expected. For the N-wave signatures the effect of rise time, for constant peak overpressure, was to decrease subjective loudness as rise time increased. Data obtained from the two shaped boom signatures indicated that substantially larger peak overpressures could be tolerated as compared to the peak overpressures for N-wave signatures having the same subjective loudness level. The actual benefits to be derived by boom shaping, however, must await the results of future detailed testing involving a wide range of candidate minimum boom signatures.

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Appendix A.- Pre-test Briefing Remarks

Instructions

You have volunteered to participate in a research program to evaluate various sounds that may be produced by aircraft. Our purpose is to study people's impressions of these sounds. To do this we have built a simulator which can create sounds similar to those produced by some aircraft. The simulator provides no risk to participants. It meets stringent safety requirements and cannot produce noises which are harmful. It contains safety features which will automatically shut the system down if it does not perform properly.

You will enter the simulator, sit in the chair, and make yourself comfortable. The door will be closed and you will hear a series of sounds. These sounds represent those you could occasionally hear during your routine daily activities. Your task will be to evaluate these sounds using a method that we will explain later. Make yourself as comfortable and relaxed as possible while the test is being conducted. You will at all times be in two-way communication with the test conductor and monitored by the overhead TV camera. You may at any time and for any reason terminate the test in either of two ways: (1) by voice communication with the test conductor or (2) by exiting the simulator.

Appendix B.- Voluntary Consent Form

VOLUNTARY CONSENT FORM FOR SUBJECTS

FOR HUMAN RESPONSE TO AIRCRAFT NOISE AND VIBRATION

I understand the purpose of the research and the technique to be used, including my participation in the research, as explained to me by the Principal Investigator (or qualified designee).

I do voluntarily consent to participate as a subject in the human response to aircraft noise experiment to be conducted at NASA Langley Research Center on ______________________________
date

I understand that I may at any time withdraw from the experiment and that I am under no obligation to give reasons for withdrawal or to attend again for experimentation.

I will undertake to obey the regulations of the laboratory and instruction of the Principal Investigator regarding safety, subject only to my right to withdraw declared above.

I affirm that, to my knowledge, my state of health has not changed since the time at which I completed and signed the medical report form required for my participation as a test subject.

____
PRINT NAME

____
SIGNATURE

Appendix C.- Specific Test Instructions

Test Instructions

Before the start of the test you will be given a short practice session to familiarize you with the test procedure. After completion of the practice session we will collect the practice scoring sheets. At that time the test conductor will be glad to answer any questions you may have concerning the test.

The procedure will involve presentation of "pairs" of sounds. Your task will be to judge which of the two sounds in the pair is louder. If you feel the first sound you hear is louder then circle "FIRST" on your scoresheet. If you feel the second sound is louder then circle "SECOND" on your scoresheet. <u>PLEASE CIRCLE EITHER "FIRST" OR "SECOND" FOR EVERY SOUND EVEN IF YOU FEEL THEY ARE ALMOST EQUALLY LOUD.</u> Just make your best guess as to which is loudest.

This test will consist of two sessions, each containing 36 pairs of sounds. After the first session you will have a short break. When making your evaluations do not worry about "trying to be consistent" with prior evaluations that you have made. Judge each pair of sounds strictly on their own merits. Also, it is important to listen to both sounds before making your evaluations.

Appendix D.- Scoring Sheets

PRACTICE SESSION

SUBJECT #:__________
DATE : __________

Circle **FIRST** if the first sound you hear is louder.
Circle **SECOND** if the second sound you hear is louder.

1.	FIRST	SECOND	4.	FIRST	SECOND
2.	FIRST	SECOND	5.	FIRST	SECOND
3.	FIRST	SECOND	6.	FIRST	SECOND

Appendix D.- Continued

TEST NAME:____________________________________

SUBJECT #:_________
DATE : _________

Circle **FIRST** if the first sound you hear is the loudest.
Circle **SECOND** if the second sound you hear is the loudest.

1.	FIRST	SECOND	19.	FIRST	SECOND
2.	FIRST	SECOND	20.	FIRST	SECOND
3.	FIRST	SECOND	21.	FIRST	SECOND
4.	FIRST	SECOND	22.	FIRST	SECOND
5.	FIRST	SECOND	23.	FIRST	SECOND
6.	FIRST	SECOND	24.	FIRST	SECOND
7.	FIRST	SECOND	25.	FIRST	SECOND
8.	FIRST	SECOND	26.	FIRST	SECOND
9.	FIRST	SECOND	27.	FIRST	SECOND
10.	FIRST	SECOND	28.	FIRST	SECOND
11.	FIRST	SECOND	29.	FIRST	SECOND
12.	FIRST	SECOND	30.	FIRST	SECOND
13.	FIRST	SECOND	31.	FIRST	SECOND
14.	FIRST	SECOND	32.	FIRST	SECOND
15.	FIRST	SECOND	33.	FIRST	SECOND
16.	FIRST	SECOND	34.	FIRST	SECOND
17.	FIRST	SECOND	35.	FIRST	SECOND
18.	FIRST	SECOND	36.	FIRST	SECOND

TABLE 1.- PARAMETERS FOR COMPARISON SONIC BOOMS

Boom Type	Rise Time, ms	Peak Overpressure, ΔP_{max}, Pascals					
		1	2	3	4	5	6
N-Wave	1	16.3	20.6	25.8	33.0	41.2	52.1
	2	22.5	28.2	35.9	44.5	56.5	70.8
	4	27.3	34.0	43.1	54.5	68.4	86.1
	8	38.8	48.8	61.2	77.5	97.1	123.4
Shaped	2*	39.7	49.8	63.1	78.5	96.6	145.0
	2*	69.4	87.6	108.1	131.1	156.0	177.5

*Initial Rise Time, Secondary Rise Time = 50 ms

TABLE 2.- CORRELATION COEFFICIENTS BETWEEN CALCULATED METRICS AND (1) PROPORTION OF RATINGS LOUDER THAN STANDARD SIGNATURE AND (2) LOGIT SCORES

Boom #	Rise Time, ms	Proportion (1)			Logit Score (2)		
		SLC	SLA	PL	SLC	SLA	PL
1	1	0.957	0.958	0.955	0.947	0.948	0.946
2	2	0.945	0.945	0.944	0.983	0.983	0.982
3	4	0.971	0.971	0.971	0.986	0.986	0.985
4	8	0.988	0.989	0.989	0.987	0.986	0.985
5	2*	0.985	0.984	0.984	0.991	0.991	0.961
6	2*	0.980	0.982	0.982	0.996	0.995	0.996
ALL BOOMS		0.764	0.925	0.957	0.752	0.941	0.962

*Initial Rise Time of Shaped Boom

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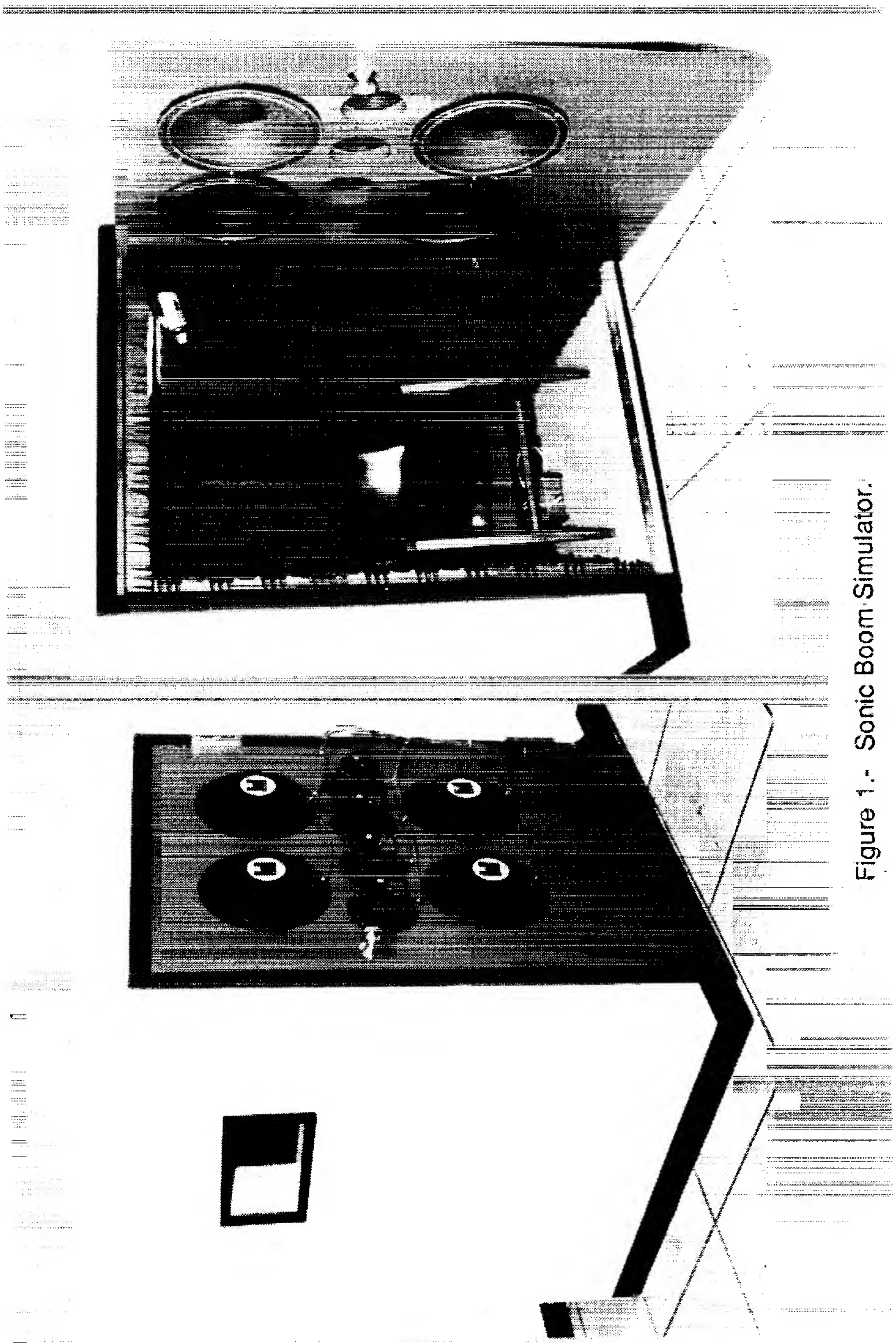

Figure 1.- Sonic Boom Simulator.

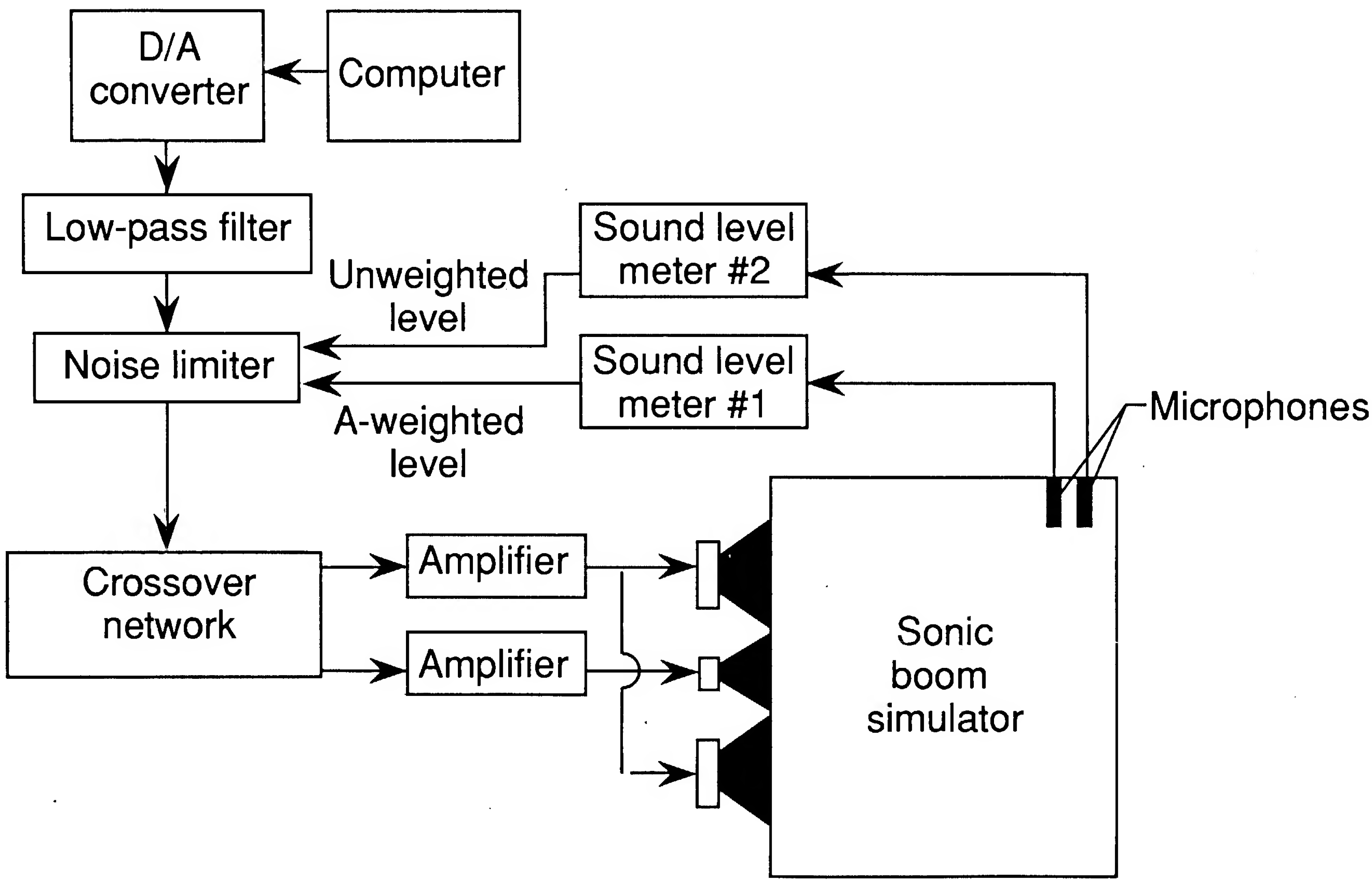

Figure 2.- Sonic Boom Generation and Monitoring System.

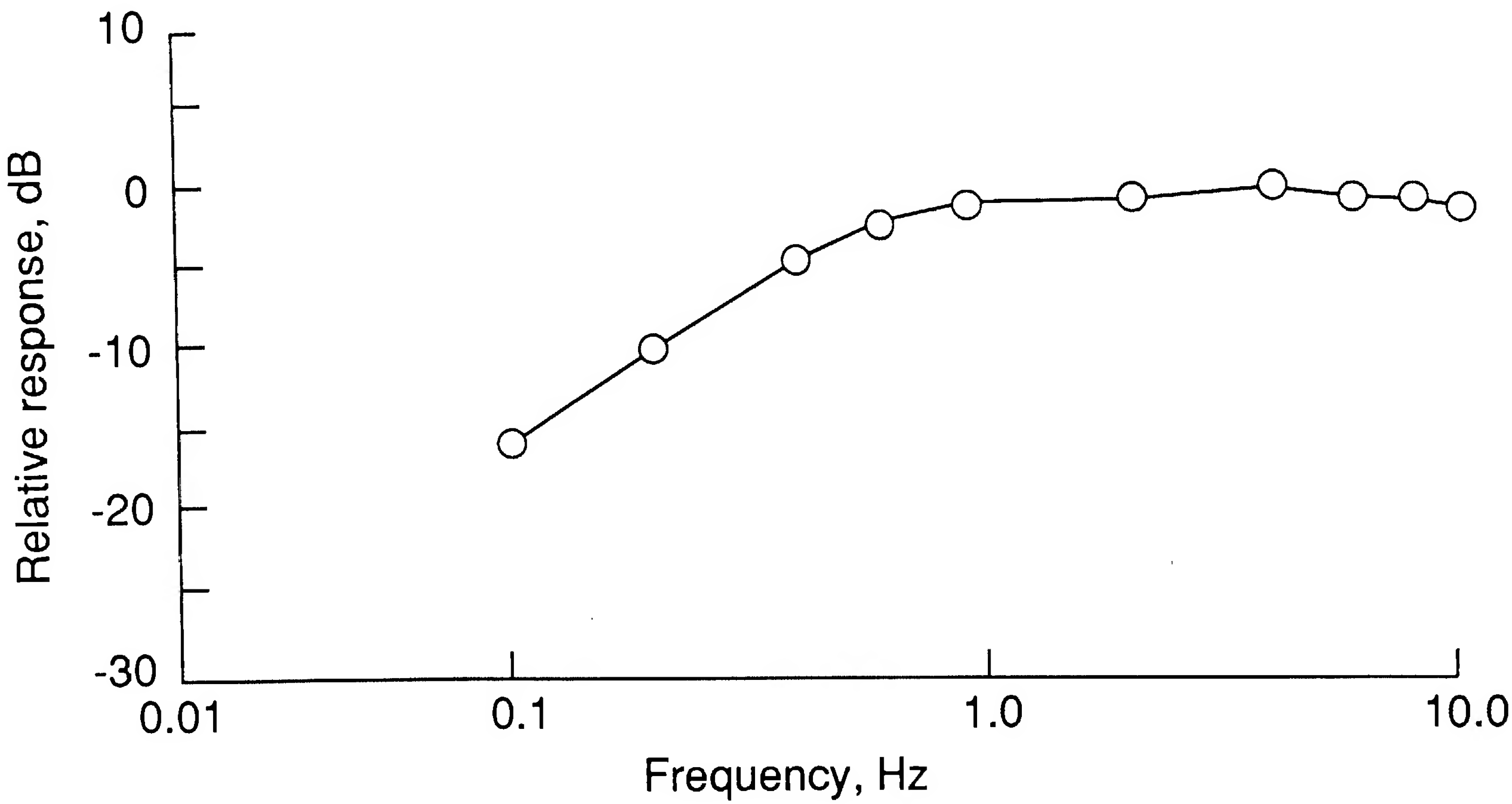

Figure 3.- Frequency Response of Sonic Boom Simulator at Low Frequencies.

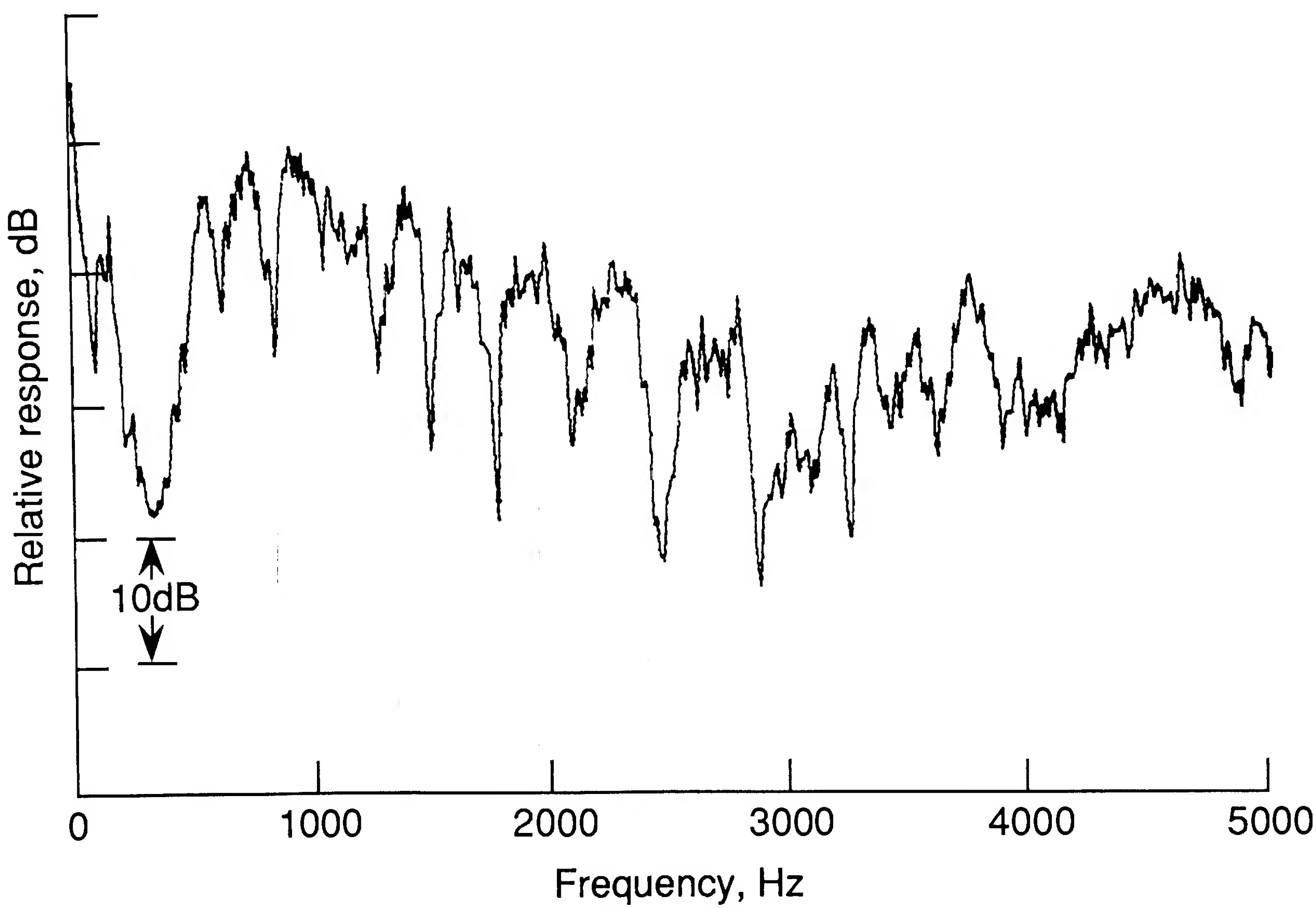

Figure 4.- Frequency Response of Sonic Boom Simulator at High Frequencies.

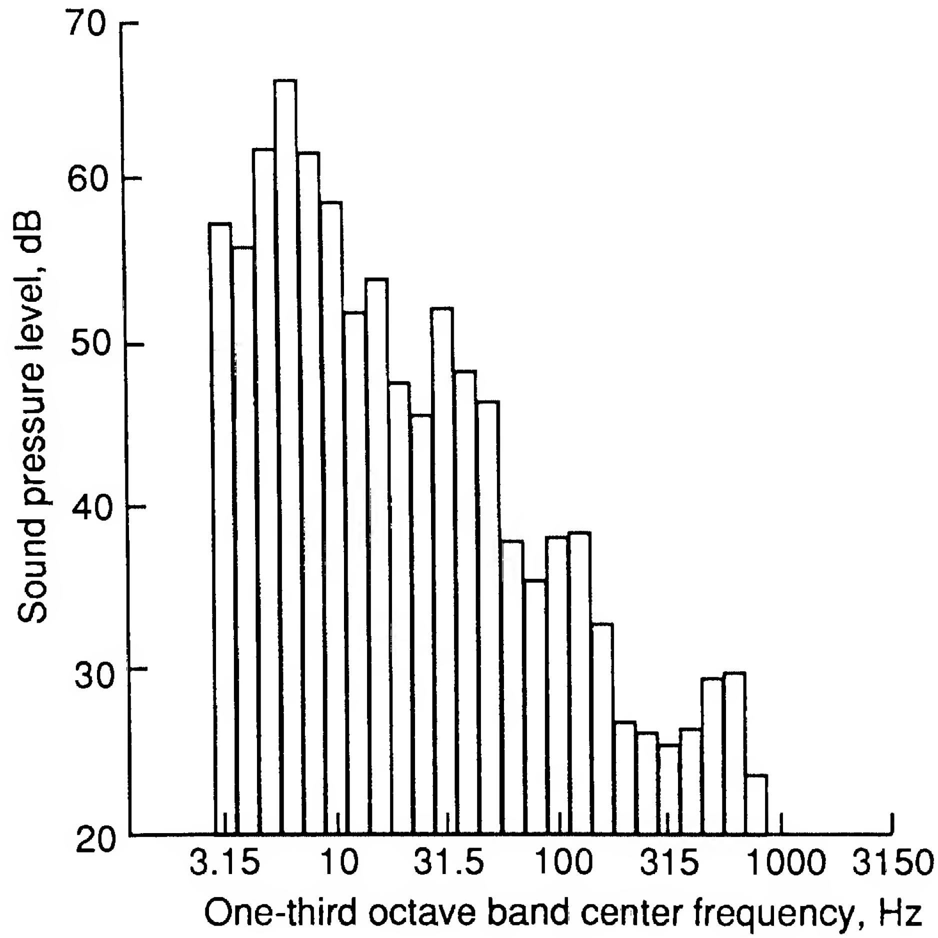

Figure 5.- Ambient Noise Level in Simulator with Sound System Off. (SLA=34 dB)

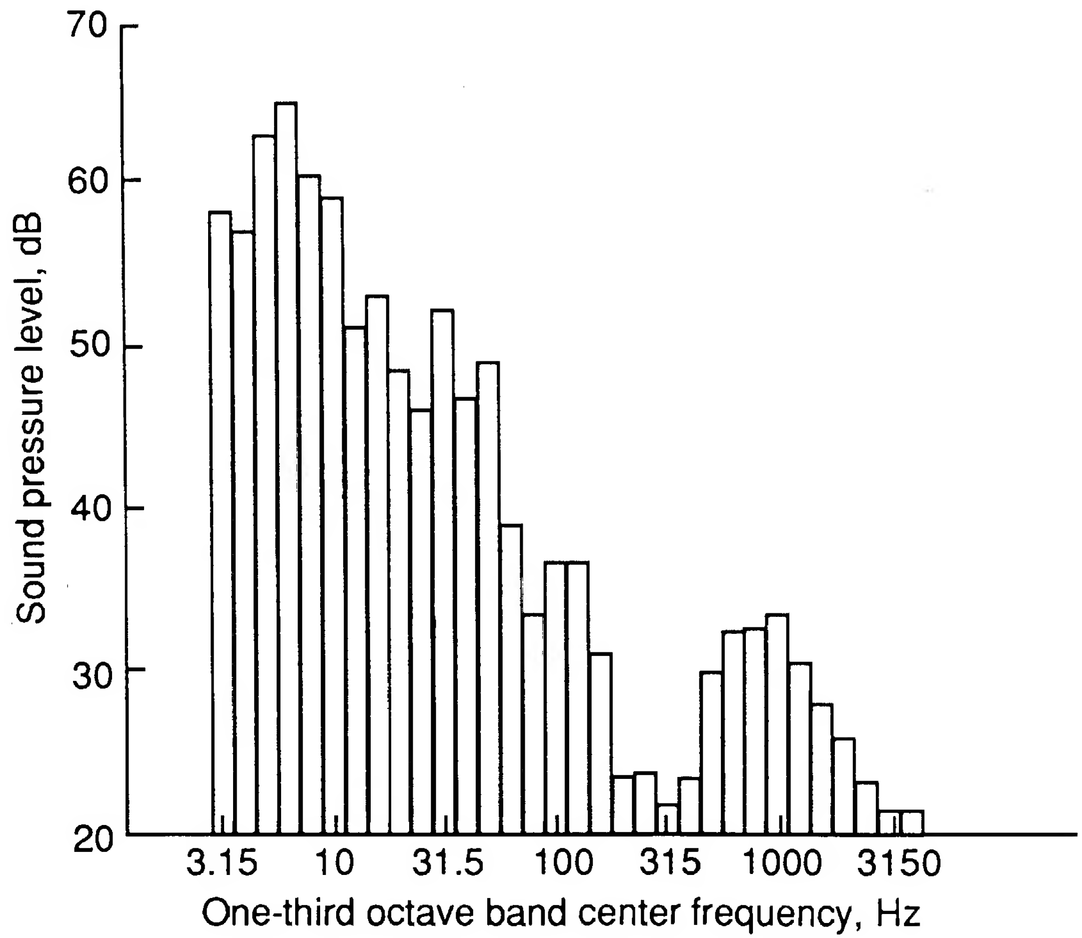

Figure 6.- Ambient Noise Level in Simulator with Sound System On. (SLA=40 dB)

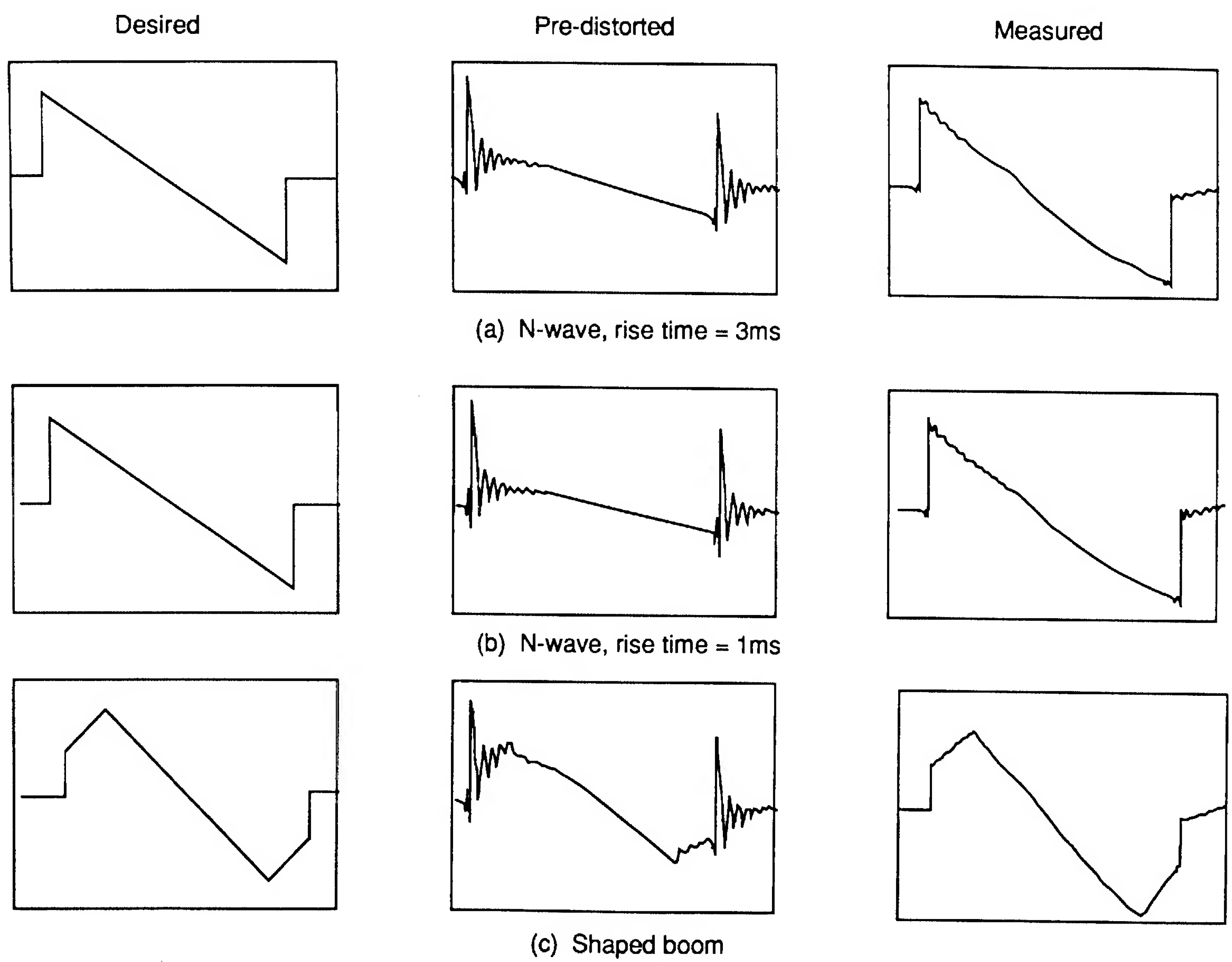

Figure 7.- Examples of Desired, Pre-distorted, and Measured Sonic Boom Signatures.

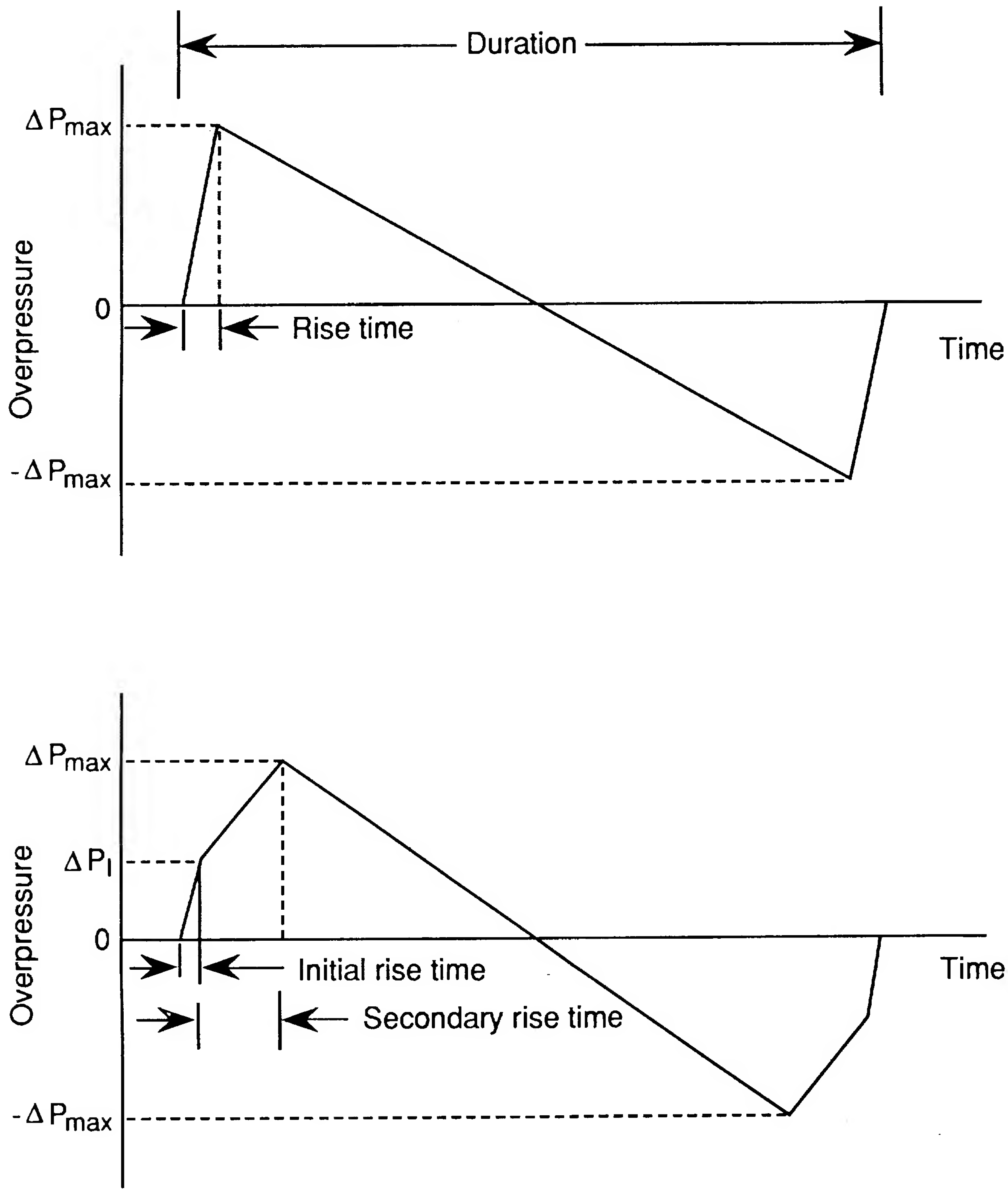

Figure 8.- Parameters for N-wave (Top) and Shaped (Bottom) Sonic Boom Signatures.

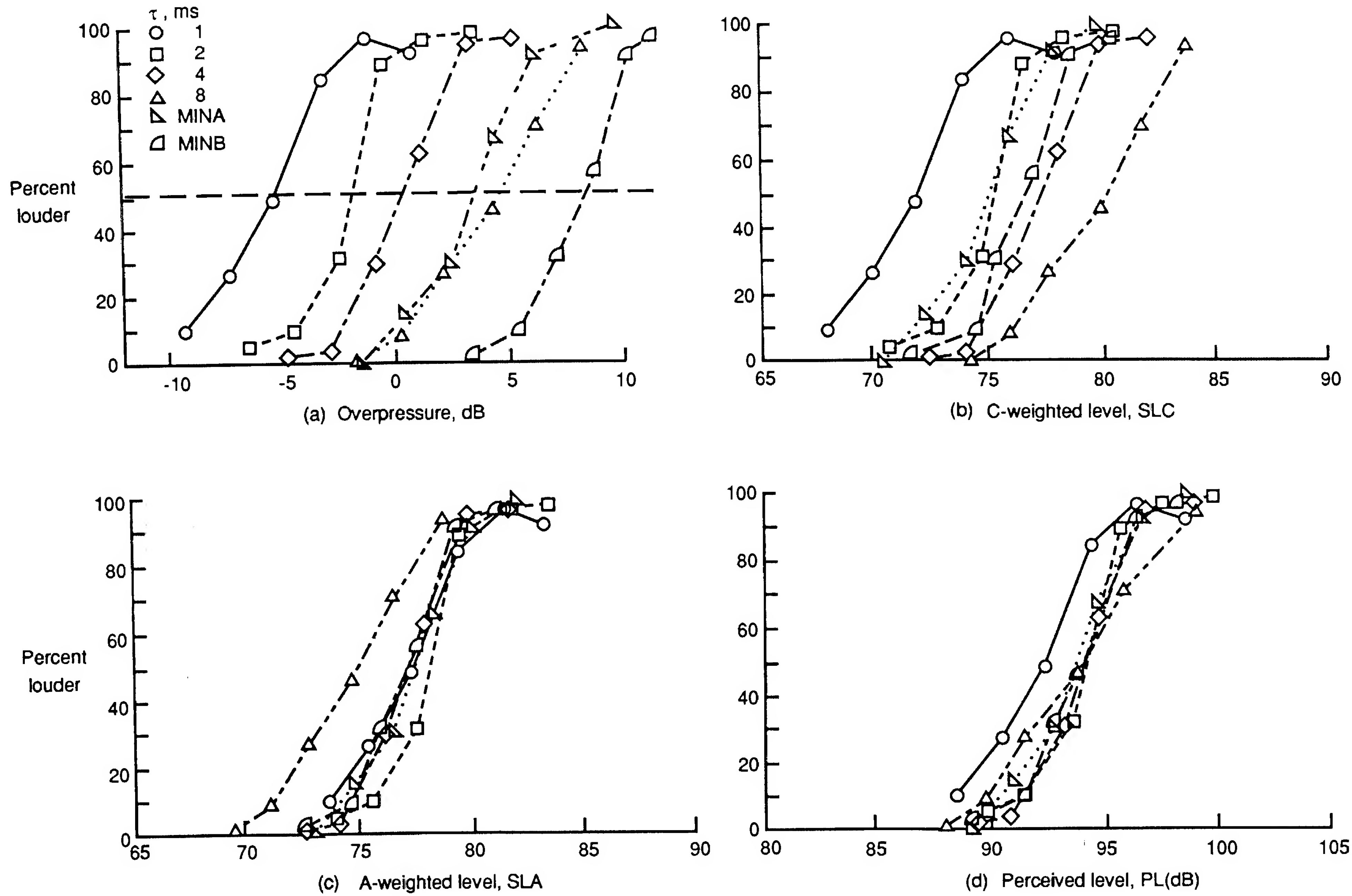

Figure 9.- Percent of Responses Indicating Comparison Booms Were Louder Than the Standard Boom for Various Metrics.

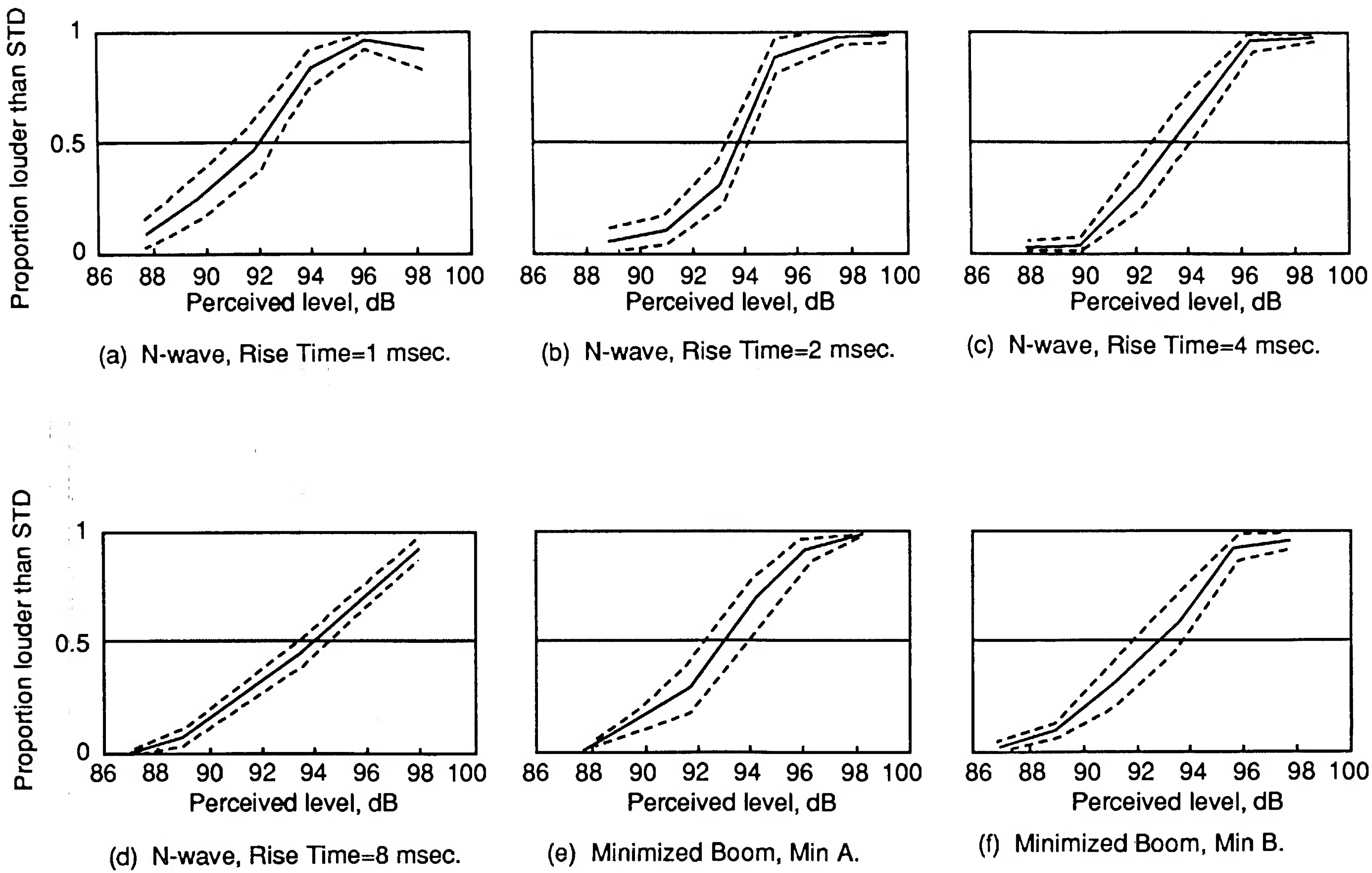

Figure 10.- Ninety-five (95) Percent Confidence Intervals on Proportion of Responses Rated Louder Than the Standard Boom Signature for Each Signature Shape.

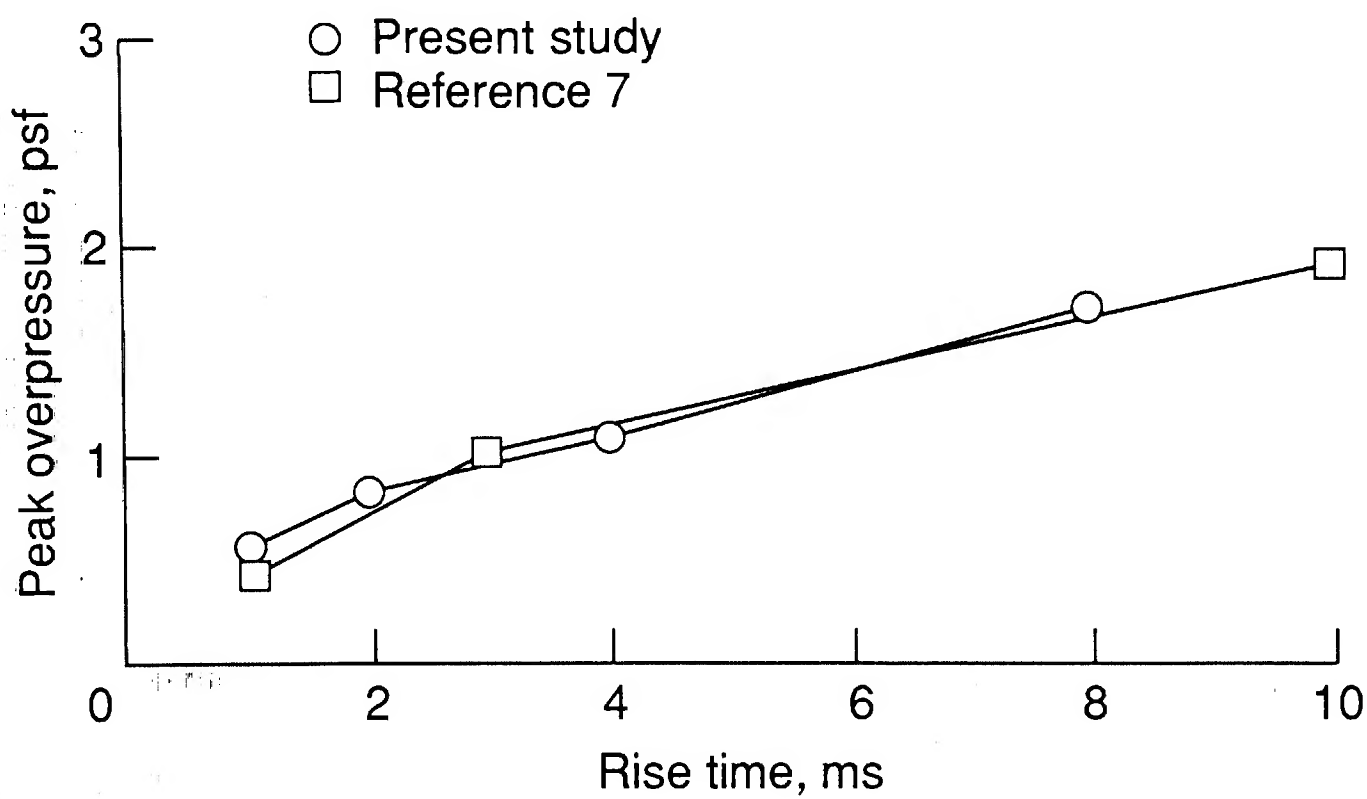

Figure 11.- Comparison of Equal Loudness Curves (Peak Overpressure vs. Rise Time) of Present Study with the Results of Reference 7.

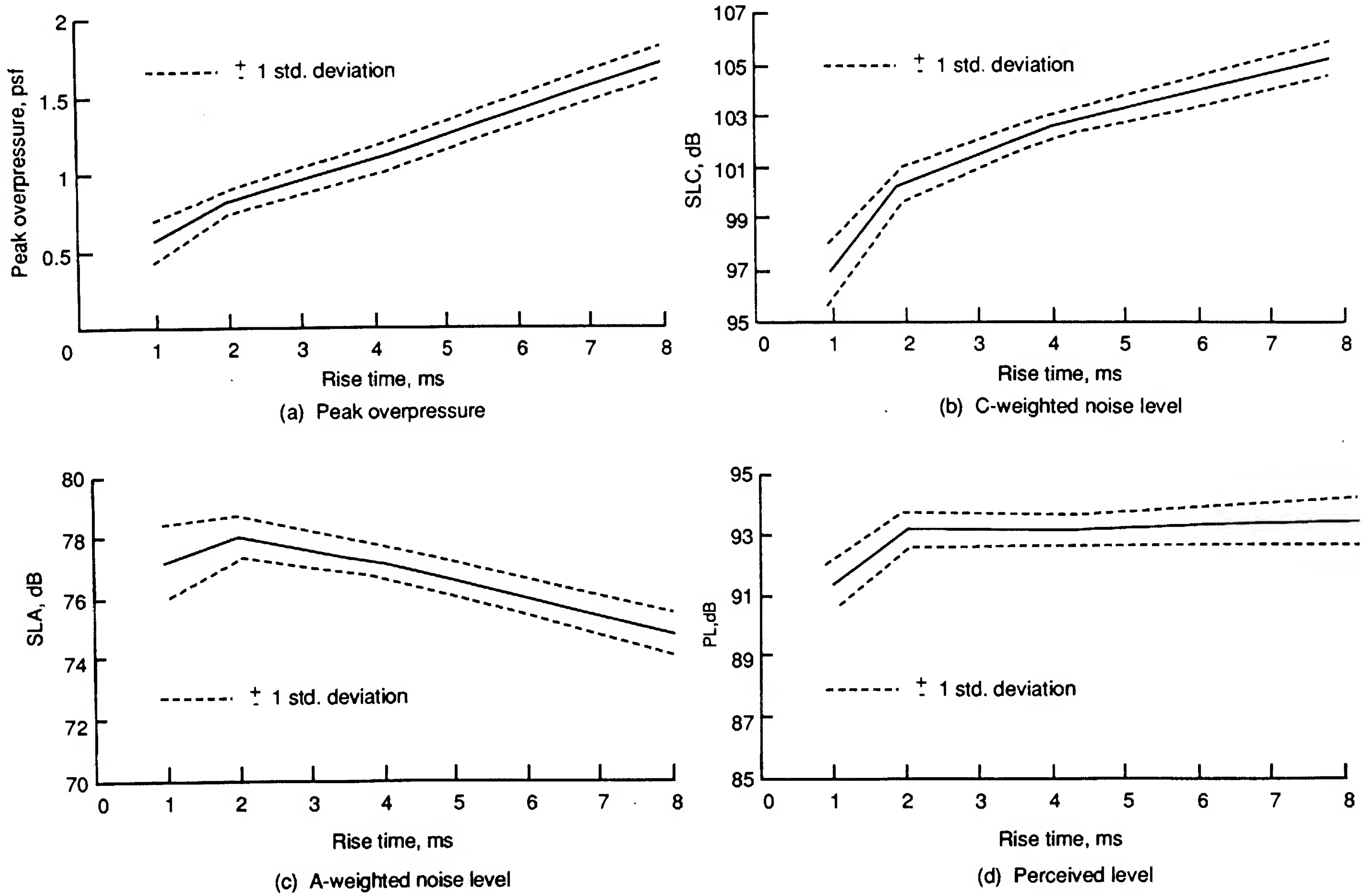

Figure 12.- Relationship Between Metric Level and Rise Time for the N-wave Signatures of the Present Study.

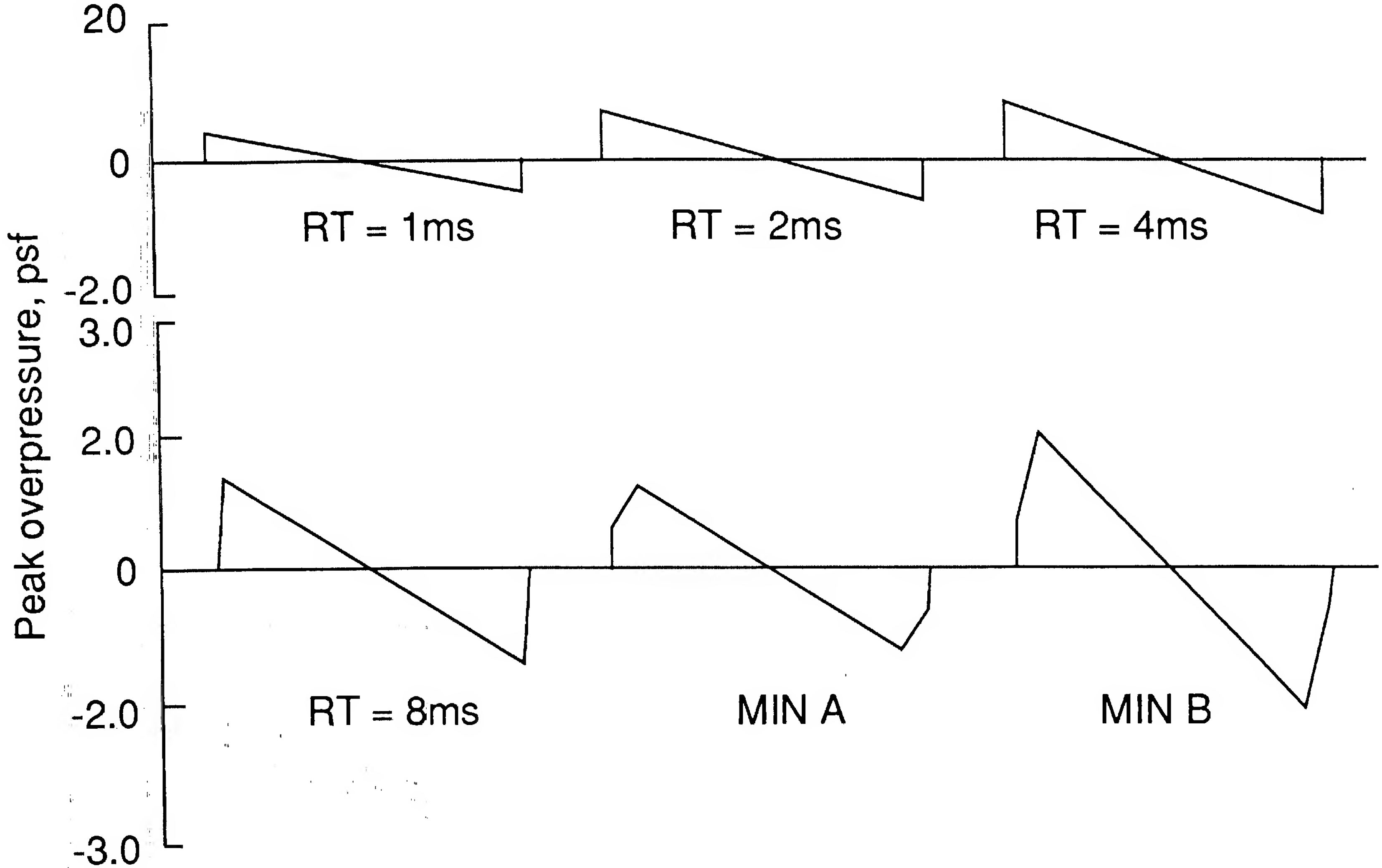

Figure 13.- Sonic Boom Signatures Judged Equally Loud.

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16. Abstract
A man-rated and computer-driven sonic boom simulator which has been constructed and placed in operational use at Langley Research Center is described. The simulator is used to study human subjective reactions to sonic booms and has the capability of producing a wide range of signatures under controlled conditions. Results are presented to illustrate the capability of the simulator to generate user-specified N-wave and shaped booms having rise times as low as 0.5 milliseconds and peak overpressures up to 191 Pa (4 psf).

The validity of the simulator as a laboratory research tool for studying human subjective response to sonic booms was demonstrated by successful completion of a preliminary test designed to compare loudness of N-wave sonic booms with results obtained by other investigators. Excellent agreement of the preliminary test data with existing data was observed. This provided confidence in the experimental methodology and established the simulator as a viable tool for performing detailed evaluations of sonic boom loudness and acceptability within the laboratory environment.

17. Key Words (Suggested by Author(s))
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